Chapter 2
Planning, Design, and Accuracy Requirements

2-1. Standards for Deformation Surveys

a. General. This chapter provides guidance for planning and implementing structural deformation surveys on US Army Corps of Engineers civil works projects. It discusses criteria and objectives used for designing geodetic monitoring networks and for developing reliable and economical measurement schemes based on precise engineering surveying methods. Monitoring provides engineering data and analysis for verifying design parameters, for construction safety, for periodic inspection reports, and for regular maintenance operations. Safety, economical design of man-made structures, efficient functioning and fitting of structural elements, environmental protection, and development of mitigative measures in the case of natural disasters (land slides, earthquakes, liquefaction of earth dams, etc.) requires a good understanding of causes (loads) and the mechanism of deformation, which can be achieved only through the proper measurement and analysis of deformable bodies.

b. Dam safety. US Army Corps of Engineers owns and operates a wide range of large engineering structures, including major infrastructure facilities for navigation, flood protection, and large dams. The responsibility to minimize the risk to the public is critical due to the potential loss of life and property that a structural failure could cause. USACE dams and reservoirs must be inspected so that their structural condition and design assumptions can be evaluated and verified. As a result of major disasters in the United States, the federal government revised laws for supervision of the safety of dams and reservoirs. The Dam Inspection Act, PL 92-367, 8 August 1972, authorized the Secretary of the Army, acting through the Chief of Engineers, to undertake a national program of inspection of dams.

c. Engineer regulations. Standards for conducting instrumentation surveys and for periodic inspections are contained in the following publications.

- ER 1110-2-100, Periodic Inspection and Continuing Evaluation of Completed Civil Works Structures
- ER 1110-2-110, Instrumentation for Safety--Evaluation of Civil Works Projects
- EP 1110-2-13, Dam Safety Preparedness

Guidance for Civil Works projects provides for an adequate level of instrumentation to enable designers to monitor and evaluate the safety of the structures, and to address the need for inspection and evaluation for stability and operational adequacy, as well as safety. ER 1110-2-100 states that a systematic plan will be established for the inspection of those features relating to safety and stability of the structure and to the operational adequacy of the project. Operational adequacy means the inspecting, testing, operating, and evaluation of those components of the project whose failure to operate properly would impair the operational capability and/or usability of the structure. Appendix A of ER 1110-2-100 addresses provisions to collect and permanently retain specific engineering data relating to the project structure and examine records that detail the principal design assumptions and stability, stress analysis, slope stability, and settlement analyses.

d. Specialized standards. Federal geospatial data standards, established in OMB Circular No. A-16, Coordination of Surveying, Mapping, and Related Spatial Data Activities, provide for activities conducted to meet special agency program needs. USACE engineering and construction guidance for geospatial data products prescribes voluntary industry standards and consensus standards, except where they are non-existent, inappropriate, or do not meet a project's functional requirement. Specialized standards for conducting deformation surveys are justified as long as products are consistent with effective government wide coordination and efficient, economical service to the general public. Deformation monitoring often requires specialized surveying methods that are planned and executed according to specialized techniques and procedures.

2-2. Accuracy Requirements for Performing Deformation Surveys

a. General. The following table provides guidance on the accuracy requirements for performing deformation surveys. These represent either absolute or relative movement accuracies on target points that should be attained from survey observations made from external reference points. The accuracy by which the external reference network is established and periodically monitored for stability should exceed these accuracies. Many modern survey systems (e.g., electronic total stations, digital levels, GPS, etc.) are easily capable of meeting or exceeding the accuracies shown below. However, it is important that accuracy criteria must be defined relative to the particular structure's requirements, not the capabilities of a survey instrument or system.

Table 2-1. Accuracy Requirements for Structure Target Points (95% RMS)

Concrete Structures — Dams, Outlet Works, Locks, Intake Structures:	
Long-Term Movement	± 5-10 mm
Relative Short-Term Deflections Crack/Joint movements Monolith Alignment	± 0.2 mm
Vertical Stability/Settlement	± 2 mm
Embankment Structures — Earth-Rockfill Dams, Levees:	
Slope/crest Stability	± 20-30 mm
Crest Alignment	± 20-30 mm
Settlement measurements	± 10 mm
Control Structures — Spillways, Stilling Basins, Approach/Outlet Channels, Reservoirs	
Scour/Erosion/Silting	± 0.2 to 0.5 foot

b. Accuracy design examples. As an example to distinguish between instrument accuracy and project accuracy requirements, an electronic total station system can measure movement in an earthen embankment to the ±0.005-foot level. Thus, a long-term creep of say 3.085 feet can be accurately measured. However, the only significant aspect of the 3.085-foot measurement is the fact that the embankment has sloughed "3.1 feet" -- the ±0.001-foot resolution (precision) is not significant and should not be observed even if available with the equipment. As another example, relative crack or monolith joint micrometer measurements can be observed and recorded to ±0.001-inch precision. However, this precision is not necessarily representative of an absolute accuracy, given the overall error budget in the micrometer measurement system, measurement plugs, etc. Hydraulic load and temperature influences can radically change these short-term micrometer measurements at the 0.01 to 0.02-inch level, or more. Attempts to observe and record micrometer measurements to a 0.001-inch precision with a ±0.01-inch temperature fluctuation are wasted effort on this typical project.

2-3. Overview of Deformation Surveying Design

a. General. USACE Engineering Divisions and Districts have the responsibility for formulating inspection plans, conducting inspections, processing and analyzing instrument observations, evaluating the condition of the structures, recommending inspection schedules, and preparing inspection and evaluation reports. This section presents information to aid in fulfilling these objectives.

b. Monitoring plan. Each monitored structure should have a technical report or design memorandum published for the instrumentation and/or surveying scheme to document the monitoring plan and its intended performance. A project specific measurement scheme and its operating procedures should be developed for the monitoring system (Figure 2-1). Separate designs should be completed for the instrumentation plan and for the proposed measurement scheme.

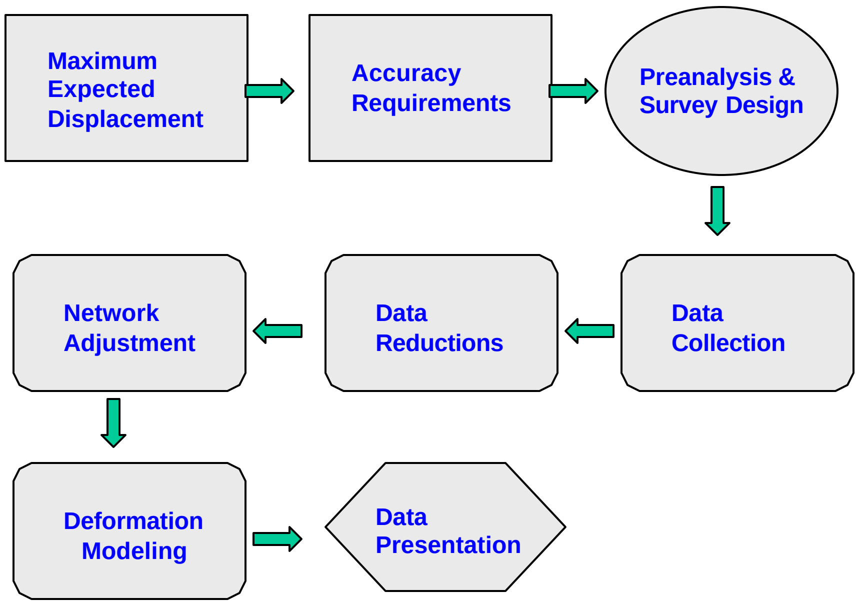

Figure 2-1. Deformation Survey Data Flow

(1) Survey system design. Although accuracy and sensitivity criteria may differ considerably between various monitoring applications, the basic principles of the design of monitoring schemes and their geometrical analysis remain the same. For example, a study on the stability of magnets in a nuclear accelerator may require determination of relative displacements with an accuracy of $\pm$0.05 mm while a settlement study of a rock-fill dam may require only $\pm$10 mm accuracy. Although in both cases, the monitoring techniques and instrumentation may differ, the same basic methodology applies to the design and analysis of the deformation measurements.

(a) Instrumentation plan (design). The instrumentation plan is mainly concerned with building or installing the physical network of surface movement points for a monitoring project. Contained in the instrumentation plan are specifications, procedures, and descriptions for:

- Required equipment, supplies, and materials,
- Monument types, function, and operating principles,
- Procedures for the installation and protection of monuments,
- Location and coverage of monitoring points on the project,
- Maintenance and inspection of the monitoring network.

The plan contains drawings, product specifications, and other documents that completely describe the proposed instrumentation, and methods for fabrication; testing; installation; and protection and maintenance of instruments and monuments.

(b) Measurement scheme (design). The design of the survey measurement scheme should include analysis and specifications for:

- Predicted performance of the structure,
- Measurement accuracy requirements,
- Positioning accuracy requirements,
- Number and types of measurements,
- Selection of instrument type and precision,
- Data collection and field procedures,
- Data reduction and processing procedures,
- Data analysis and modeling procedures,
- Reporting standards and formats,
- Project management and data archiving.

The main technique used to design and evaluate measurement schemes for accuracy is known as "network preanalysis." Software applications specially written for preanalysis and adjustment are used to compute expected error and positioning confidence for all surveyed points in the monitoring network (see Chapter 9).

(2) Data collection. The data collection required on a project survey is specifically prescribed by the results of network preanalysis. The data collection scheme must provide built-in levels of both accuracy and reliability to ensure acceptance of the raw data.

(a) Accuracy. Achieving the required accuracy for monitoring surveys is based on instrument performance and observing procedures. Minimum instrument resolution, data collection options, and proper operating instructions are determined from manufacturer specifications. The actual data collection is executed according to the results of network preanalysis so that the quality of the results can be verified during data processing and post-analysis of the network adjustment.

(b) Reliability. Reliability in the raw measurements requires a system of redundant measurements, sufficient geometric closure, and strength in the network configuration. Geodetic surveying methods can yield high redundancy in the design of the data collection scheme.

(3) Data processing. Raw survey data must be converted into meaningful engineering values during the data processing stage. Several major categories of data reductions are:

- Applying pre-determined calibration values to the raw measurements,
- Finding mean values for repeated measurements of the same observable,
- Data quality assessment and statistical testing during least squares adjustment,
- Measurement outlier detection and data cleaning prior to the final adjustment.

Procedures for data reductions should be based on the most rigorous formulas and data processing techniques available. These procedures are applied consistently to each monitoring survey to ensure comparable results. Network adjustment software based on least squares techniques is strongly recommended for data processing. Least squares adjustment techniques are used to compute the coordinates and survey accuracy for each point in the monitoring network. Network adjustment processing also identifies measurement blunders by statistically testing the observation residuals.

(4) Data analysis. Geometric modeling is used to analyze spatial displacements (see Chapter 11). General movement trends are described using a sufficient number of discrete point displacements (d_n):

$d_n(\Delta x, \Delta y, \Delta z)$ for n = point number

Point displacements are calculated by differencing the adjusted coordinates for the most recent survey campaign (*f*), from the coordinates obtained at some reference time (*i*), for example:

$\Delta x = x_f - x_i$ is the x coordinate displacement
$\Delta y = y_f - y_i$ is the y coordinate displacement
$\Delta z = z_f - z_i$ is the z coordinate displacement
$\Delta t = t_f - t_i$ is the time difference between surveys.

Each movement vector has magnitude and direction expressed as point displacement coordinate differences. Collectively, these vectors describe the displacement field over a given time interval. Displacements that exceed the amount of movement expected under normal operating conditions will indicate possible abnormal behavior. Comparison of the magnitude of the calculated displacement and its associated survey accuracy indicates whether the reported movement is more likely due to survey error:

$$|d_n| < (e_n)$$

where

$|d_n| = \text{sqrt}(\Delta x^2 + \Delta y^2 + \Delta z^2)$ for point n, is the magnitude of the displacement,

(e_n) = max dimension of combined 95% confidence ellipse for point n $= (1.96)\ \text{sqrt}(\sigma_f^{\,2} + \sigma_i^{\,2})$,

and

σ_f is the standard error in position for the (final) or most recent survey,
σ_i is the standard error in position for the (initial) or reference survey.

For example, if the adjusted coordinates for point n in the initial survey were:

$x_i = 1000.000$ m
$y_i = 1000.000$ m
$z_i = 1000.000$ m

and the adjusted coordinates for the same point in the final survey were:

$x_f = 1000.006$ m
$y_f = 1000.002$ m
$z_f = 1000.002$ m

then the calculated displacement components for point n would be:

$\Delta x = 6$ mm
$\Delta y = 2$ mm
$\Delta z = 2$ mm

Assuming that the horizontal position has a standard deviation of σ_h = 1.5 mm for both surveys, and similarly the vertical position has a standard deviation of σ_v = 2.0 mm, as reported from the adjustment results, then the combined (95 percent) confidence in the horizontal displacement would be:

$$(1.96) \text{ sqrt } (\sigma_f^{\,2} + \sigma_i^{\,2}) = (1.96) \text{ sqrt } (2.25 + 2.25) \sim 4.2 \text{ mm at 95\% confidence}$$

The magnitude of the horizontal displacement is:

$$|d_h| = \text{sqrt } (\Delta x^2 + \Delta y^2) = \text{sqrt } (36 + 4) = 6.3 \text{ mm}$$

These results show that the horizontal component exceeds the expected survey error margin and is likely due to actual movement of point *n* in the horizontal plane.

Confidence in the vertical displacement would be:

$$(1.96) \text{ sqrt } (\sigma_f^{\,2} + \sigma_i^{\,2}) = (1.96) \text{ sqrt } (4 + 4) \sim 5.5 \text{ mm at 95\% confidence}$$

The magnitude of the vertical displacement is:

$$|d_v| = 2.0 \text{ mm}$$

The magnitude of the vertical displacement is much smaller than the confidence in the vertical displacement, and it therefore does not indicate a significant vertical movement. If the structure were to normally experience cyclic movement of 10 mm (horizontally) and 1 mm (vertically) over the course of one year, and if our example deformation surveys were made six months apart, then the above results would be consistent with expected behavior. Specialized methods of geometrical analysis exist to carry out more complex deformation modeling, and it is sometimes possible to identify the causes of deformation based on comparing the actual displacements to alternative predicted displacement modes for the specific type of structure under study. Refer to Chapter 11 for a more detailed discussion.

(5) Data presentation. Survey reports for monitoring projects should have a standardized format. Reports should contain a summary of the results in both tabulated and graphical form (Chapter 12). All supporting information, analyses, and data should be documented in an appendix format. Conclusions and recommendations should be clearly presented in an executive summary.

(6) Data management. Survey personnel should produce hardcopy survey reports and complete electronic copies of these reports. Survey data and processed results should be archived, indexed, and cross-referenced to existing structural performance records. These should be easily located and retrievable whenever the need arises. Information management using computer-based methods is strongly recommended. One of the main difficulties with creating a data management system that includes historical data is the time and cost required to transfer existing hardcopy data into an electronic database for each project. Gradual transition to fully electronic data management on future project surveys should be adopted. Data management tools such as customized software, database software, and spreadsheet programs should be used to organize, store, and retrieve measurement data and processed results. A standard format for archiving data should be established for all monitoring projects.

c. Management plan. Sound administration and execution of the monitoring program is an integral and valuable part of the periodic inspection process. Personnel involved in the monitoring and instrumentation should maintain a regular interaction with the senior program manager. Structural monitoring encompasses a wide range of tasks performed by specialists in different functional areas. All participants should have a general understanding of requirements for the complete evaluation process.

- General Engineering for planning and monitoring requests, preparation/presentation of data and results, and quality assurance measures,

- Surveying for data collection (in-house or contract requirements), data reduction, processing, network adjustment, quality assurance, and preparing survey reports,

- Geotechnical and Structural Engineering for analysis and evaluation of results and preparation of findings and recommendations,

- Technical Support for data management, archiving, computer resources, archiving final reports, and electronic information support.

Safety requires consideration of more than just technical factors. Systems should be in place so that any voice within the organization can be heard. Even experts can make mistakes and good ideas can come from any level within an organization. Meetings and/or site visits including all participants are held to ensure that information flows freely across internal boundaries. Integration of separate efforts should be on going and seamless rather than simply gluing together individual final products.

d. External review. An organization must be willing to accept, in fact it should seek, the independent review of its engineering practices. Large structures require defensive engineering that considers a range of circumstances that might occur that threatens their safety. A contingency plan to efficiently examine and assess unexpected changes in the behavior of the structure should be in place. Outside experts should be consulted from time-to-time, especially if a project structure exhibits unusual behavior that warrants specialized measurement and analysis.

2-4. Professional Associations

a. General. The development of new methods and techniques for monitoring and analysis of deformations and the development of methods for the optimal modeling and prediction of deformations have been the subject of intensive studies by many professional groups at national and international levels.

b. Organizations. Within the most active international organizations that are involved in deformation studies one should list:

- International Federation of Surveyors (FIG) Commission 6 which has significantly contributed to the recent development of new methods for the design and geometrical analysis of integrated deformation surveys and new concepts for analyses and modeling of deformations;

- International Commission on Large Dams (ICOLD) with its Committee on Monitoring of Dams and their Foundations;

- International Association of Geodesy (IAG) Commission on Recent Crustal Movements, concerning geodynamics, tectonic plate movement, and modeling of regional earth crust deformation.

- International Society for Mine Surveying (ISM) Commission 4 on Ground Subsidence and Surface Protection in mining areas;

- International Society for Rock Mechanics (ISRM) with overall interest in rock stability and ground control; and

- International Association of Hydrological Sciences (IAHS), with work on ground subsidence due to the withdrawal of underground liquids (water, oil, etc.).

2-5. Causes of Dam Failure

a. Concrete structures. Deformation in concrete structures is mainly elastic and for large dams highly dependent on reservoir water pressure and temperature variations. Permanent deformation of the structure can sometimes occur as the subsoil adapts to new loads, concrete aging, or foundation rock fatigue. Such deformation is not considered unsafe if it does not go beyond a pre-determined critical value. Monitoring is typically configured to observing relatively long-term movement trends, including, abnormal settlements, heaving, or lateral movements. Some ways concrete dams can fail are:

- Uplift at the base of gravity dams leading to overturning and downstream creep.
- Foundation failure or buttress collapse in single or multiple arched dams
- Surrounding embankments that are susceptible to internal erosion.

b. Embankment structures. Deformation is largely inelastic with earthen dams characterized by permanent changes in shape. Self-weight of the embankment and the hydrostatic pressure of the reservoir water force the fill material and the foundation (if it consists of soil) to consolidate resulting in vertical settlement of the structure. Reservoir water pressure also causes permanent horizontal deformation mostly perpendicular to the embankment centerline. Some causes of damage to earthen dams are:

- Construction defects that cause the structure to take on anisotropic characteristics over time,
- Internal pressures and paths of seepage resulting in inadequately controlled interstitial water.

Usually these changes are slow and not readily discerned by visual examination. Other well-known causes of failure in earthen dams are overtopping at extreme flood stage and liquefaction due to ground motion during earthquakes.

c. Structural distress. The following warning signs are evidence for the potential failure of dams.

- Significant sloughs, settlement, or slides in embankments such as in earth or rockfill dams,
- Movement in levees, bridge abutments or slopes of spillway channels, locks, and abutments,
- Unusual vertical or horizontal movement or cracking of embankments or abutments,
- Sinkholes or localized subsidence in the foundation or adjacent to embankments and structures,
- Excessive deflection, displacement, or vibration of concrete structures
- Tilting or sliding of intake towers, bridge piers, lock wall, floodwalls),
- Erratic movement, binding, excessive deflection, or vibration of outlet and spillway gates,
- Significant damage or changes in structures, foundations, reservoir levels, groundwater conditions and adjacent terrain as a result of seismic events of local or regional areas,
- Other indications of distress or potential failure that could inhibit the operation of a project or endanger life and property.

2-6. Foundation Problems in Dams

a. General. Differential settlement, sliding, high piezometric pressures, and uncontrolled seepage are common evidences of foundation distress. Cracks in the dam, even minor ones, can indicate a foundation problem. Clay or silt in weathered joints can preclude grouting and eventually swell the crack enlarging it and causing further stress. Foundation seepage can cause internal erosion or solution. Potential erosion of the foundation must be considered as erosion can leave collapsible voids. Actual deterioration may be evidenced by increased seepage, by sediment in seepage water, or an increase in soluble materials disclosed by chemical analyses. Materials vulnerable to such erosion include dispersive clays, water reactive shales, gypsum and limestone.

b. Consolidation. Pumping from underground can cause foundation settlement as the supporting water pressure is removed or the gradient changed. Loading and wetting will also cause the pressure gradient to change, and may also cause settlement or shifting. The consequent cracking of the dam can create a dangerous condition, especially in earthfills of low cohesive strength. Foundations with low shear strength or with extensive seams of weak materials such as clay or bentonite may be vulnerable to sliding. Shear zones can also cause problems at dam sites where bedding plane zones in sedimentary rocks and foliation zones in metamorphics are two common problems. An embankment may be most vulnerable at its interface with rock abutments. Settlement in rockfill dams can be significantly reduced if the rockfill is mechanically compacted. In some ways, a compacted earth core is superior to a concrete slab as the impervious element of a rockfill dam. If the core has sufficient plasticity, it can be flexible enough to sustain pressures without significant damage. Several dam failures have occurred during initial impoundment.

c. Seepage. Water movement through a dam or through its foundation is one of the important indicators of the condition of the structure and may be a serious source of trouble. Seeping water can chemically attack the components of the dam foundation, and constant attention must be focused on any changes, such as in the rate of seepage, settlement, or in the character of the escaping water. Adequate measurements must be taken of the piezometric surface within the foundation and the embankment, as well as any horizontal or vertical distortion in the abutments and the fill. Any leakage at an earth embankment is potentially dangerous, as rapid erosion may quickly enlarge an initially minor defect.

d. Erosion. Embankments may be susceptible to erosion unless protected from wave action on the upstream face and surface runoff on the downstream face. Riprap amour stone on the upstream slope of an earthfill structure can protect against wave erosion, but can become dislodged over time. This deficiency usually can be detected and corrected before serious damage occurs. In older embankment dams, the condition of materials may vary considerably. The location of areas of low strength must be a key objective of the evaluation of such dams. Soluble materials are sometimes used in construction, and instability in the embankment will develop as these materials are dissolved over time. Adverse conditions which deserve attention include: poorly sealed foundations, cracking in the core zone, cracking at zonal interfaces, soluble foundation rock, deteriorating impervious structural membranes, inadequate foundation cutoffs, desiccation of clay fill, steep slopes vulnerable to sliding, blocky foundation rock susceptible to differential settlement, ineffective contact at adjoining structures and at abutments, pervious embankment strata, vulnerability to conditions during an earthquake.

e. Liquefaction. Hydraulic fill dams are particularly susceptible to earthquake damage. Liquefaction is a potential problem for any embankment that has continuous layers of soil with uniform gradation and of fine grain size. The Fort Peck Dam experienced a massive slide on the upstream side in 1938, which brought the hydraulic fill dam under suspicion. The investigation at the time focused blame on an incompetent foundation, but few hydraulic fills were built after the 1930's. Heavy compaction equipment became available in the 1940's, and the rolled embankment dam became the competitive alternative.

f. Concrete deterioration. Chemical and physical factors can age concrete. Visible clues to the deterioration include expansion, cracking, gelatinous discharge, and chalky surfaces.

2-7. Navigation Locks

a. Lock wall monoliths. Periodic monitoring is provided to assess the safety performance of lock structures. Instrumentation should be designed to monitor lateral, vertical, and rotational movement of the lock monoliths, although not all structural components of a lock complex (e.g., wall/monoliths, wing walls, gates, dam) may need to be monitored. Navigation locks (including access bridge piers) and their surroundings are monitored to determine the extent of any differential movements between wall monoliths, monolith tilt, sheet pile cell movement, cracking, or translation or rotation affecting sections of the lock structure.

(1) Foundation. Piezometers are used to monitor uplift pressures beneath the lock structure. Water level monitoring is made through wells fitted with a vibrating wire pressure transducer or designed for manual measurement with a portable water level indicator. Inclinometer casings are anchored in stable zones under the structure and are used to monitor lateral movement of selected monoliths. Probe readings are made at 2-ft increments to measure the slope of the casing. Foundation design concerns soil/structure interactions, pile or soil bearing strength, settlement, scour protection, stability for uplift, sliding, and overturning, slide activity below ground level, earthquake forces and liquefaction, horizontal stresses in underlying strata and residual strength, rock faults that penetrate foundation sedimentary materials, and evidence of movement in unconsolidated sediment along the rim and foundation of the surrounding basin.

(2) Expected loads. Lock structures experience dynamic loads due to hydraulic forces, seismic and ice forces, earth pressures, and thermal stresses. Static loads include weight of the structure and equipment. Horizontal water pressure and uplift on lock walls vary due to fluctuating water levels, and horizontal earth pressures and vertical loading vary with drained, saturated, or submerged backfill and siltation. Seismic forces and impact loads from collisions are accounted for in dynamic analysis for design of the structure. Loads are generated by filling and emptying system turbulence and barge mooring, ice and debris, wave pressure, wind loads, and differential water pressure on opposite sides of sheetpile cutoffs at the bottom of the lock monolith. Loads are generated by gate and bulkhead structures, machinery and appurtenant items, superstructure and bridge loads imparted to lock walls, temperature, and internal pore pressure in concrete.

(3) Dewatering maintenance. All locks have temporary closures for dewatering the lock chamber during maintenance activities or emergencies. Lock wall monitoring is conducted at both gate monoliths and selected interior chamber monoliths to detect any potential movement due to changing loads as the water level is lowered during lock chamber dewatering. Monitoring wells placed in the landside embankment are checked regularly to determine ground water levels that exert pressure on the landside wall. Monitoring surveys are conducted for measuring the lateral displacement of the lock walls with respect to each other and to stable ground. These are made continuously, and at regular time intervals until the chamber is completely dewatered.

b. Lock miter gates. Observations for distress in miter lock gates may include one or more of the following: top anchorage movement, elevation change, miter offset, bearing gaps, and downstream movement.

c. Sheet pile structures. Distress in sheet pile structures may include one or more of the following: misalignment, settlement, cavity formation, or interlock separation.

d. Rubble breakwaters and jetties. Observations for breakwaters and jetties include the seaside and leeside slopes and crest: seaside/leeside slope - protection side walls should be examined for; armor loss, armor quality defects, lack of armor contact/interlock, core exposure/loss, other slope defects.

Crest/cap - peak or topmost surface areas should be examined for breaching, armor loss, core exposure/loss. Any number of measurements may be needed to monitor the condition of breakwaters, jetties, or stone placement. These may involve either lower accuracy conventional surveying, photogrammetric, or hydrographic methods.

e. Scour monitoring. Hydrographic surveys for scour monitoring employ equipment that will produce full coverage bathymetric mapping of the area under investigation. The procedures and specifications should conform to standards referenced in EM 1110-2-1003, Hydrographic Surveying. Scour monitoring surveys should specify accuracy requirements, boundaries of coverage area, bathymetry contour interval, delivery file formats, and the required frequency of hydrographic surveying.

2-8. Deformation Parameters

a. General. The main purpose for monitoring and analysis of structural deformations is:

- To check whether the behavior of the investigated object and its environment follow the predicted pattern so that any unpredicted deformations could be detected at an early stage.

- In the case of abnormal behavior, to describe as accurately as possible the actual deformation status that could be used for the determination of causative factors which trigger the deformation.

Coordinate differencing and observation differencing are the two principal methods used to determine structural displacements from surveying data. Coordinate differencing methods are recommended for most applications that require long-term periodic monitoring. Observation differencing is mainly used for short-term monitoring projects or as a quick field check on the raw data as it is collected.

(1) Coordinate differencing. Monitoring point positions from two independent surveys are required to determine displacements by coordinate differencing. The final adjusted Cartesian coordinates (i.e., the coordinate components) from these two surveys are arithmetically differenced to determine point displacements. A major advantage of the coordinate differencing method is that each survey campaign can be independently analyzed for blunders and for data adjustment quality. However, great care must be taken to remove any systematic errors in the measurements, for example by applying all instrument calibration corrections, and by rigorously following standard data reduction procedures.

(2) Observation differencing. The method of observation differencing involves tracking changes in measurements between two time epochs. Measurements are compared to previous surveys to reveal any observed change in the position of monitoring points. Although observation differencing is efficient, and does not rely on solving for station coordinates, it has the drawback that the surveyor must collect data in an identical configuration, and with the same instrument types each time a survey is conducted.

b. Absolute displacements. Displacements of monumented points represent the behavior of the dam, its foundation, and abutments, with respect to a stable framework of points established by an external reference network.

(1) Horizontal displacements. Two-dimensional (2D) displacements are measured in a critical direction, usually perpendicular to the longitudinal axis of dam, at the crest, and other important points of embankments (abutments, toes, etc.) using conventional geodetic methods. Alignment techniques for alignment-offset measurements are made in relation to a pair of control points having well-known coordinates. Horizontal movement can also be determined with respect to plumblines having a stable anchor point (see EM 1110-2-4300, Instrumentation for Concrete Structures).

(2) Vertical displacements. Vertical displacements are measured in relation to stable project benchmarks, such as deeply anchored vertical borehole extensometers, or alternatively, to deep benchmarks located near the dam using geodetic methods (differential leveling). Hydrostatic leveling is also sometimes used to determine settlements. Settlement gauges are used to detect settlements of the foundation, or of interior structural parts which are not readily accessible (core, foundation contact). Settlements of individual layers of embankments should be monitored through settlement gauges installed in the different layers (refer to EM 1110-2-2300, Earth and Rock-Fill Dams General Design and Construction Consideration).

c. Relative displacements. These measurements are intended to determine small differential movements of points representative of the behavior of the dam, its foundation, and abutments with respect to other points on the structure, or even on the same structural element.

(1) Deflections. Relative deflections (inclinations) of a concrete dam are measured by direct or inverted plumblines. Alignment survey techniques are used in the interior galleries of dams to determine the relative movements between monoliths with respect to a horizontal reference line set along the longitudinal axis of the dam. Relative horizontal displacements of points inside embankments are detected by means of inclinometer probes sent through tubes set in drilled shafts. Foundation subsidence and tilts are measured with geodetic leveling, hydrostatic leveling, and tiltmeters. The last two are usually permanently installed in galleries.

(2) Extensions. Combinations of geodetic leveling with suspended invar wires equipped with short reading scales at different levels of the dam and connected to borehole extensometers can supply information on the relative vertical movements as well as on the absolute vertical displacements and relative tilts. Extensometers have become important instruments for measuring differential foundation movements. Strain gauges are embedded in the concrete during construction, installed on the faces of the dam after completion, or embedded in foundation boreholes. Joint measurements are justified in the case of joints separating two unsealed structures or to check grouting in dome or arch-gravity dams. Cracks are measured by the same methods with the instruments being installed on the surface.

2-9. Location of Monitoring Points

a. Normal conditions. Monitoring schemes include survey stations at the points where maximum deformations have been predicted plus a few observables at the points which, depending on previous experience, could signal any potential unpredictable behavior, particularly at the interface between the monitored structure and the surrounding material.

b. Unusual conditions. Once any abnormal deformations are noticed, then additional observables are added at the locations indicated by the preliminary analysis of the monitoring surveys as being the most sensitive to identification of causative factors.

c. Long-term monitoring. The spatial distribution of survey monuments should provide complete coverage of the structure, extending to stable areas of the project if possible. A minimum of four (4) monitoring points are recommended to model behavior in a plane section (tilts, subsidence, etc.). For linear structures, monuments are placed at intervals that provide coverage along the structure's total length, and generally not more than 100 meters apart, when using conventional instruments, to allow for measurement check ties to nearby monuments. The following are suggested guidelines for the location of survey monuments for long-term monitoring applications listed according to the type of structure. Refer also to the generalized monitoring schemes shown in Figures 2-2 through 2-6.

(1) Gravity and concrete dams. For gravity dams, each separate block should have at least one monitoring point. Tilts of the foundation should be measured at the center point for small structures, and at not less than three points for larger structures.

(2) Multiple-arch and buttress dams. Monitoring points for multiple-arch and buttress dams should be located at the head and downstream toe of each buttress. For massive buttresses and large arches, special attention should be paid to the foundations of the buttresses. If buttresses are traversed by construction joints, the behavior of joints should be observed.

(3) Arch-gravity dams and thick arch dams. Absolute displacements of dam toe and abutments are critical for arch-gravity dams and thick arch dams. For small structures, the deformation of the central block is to be monitored. For large structures the measurement of deformations in each block is required.

(4) Thin arch dams. Measurement of horizontal and vertical displacements are required along the crest for thin arch dams. Special attention should be given to the central cantilever, abutments, and abutment rock.

(5) Embankment and earthen dams. Measurement of horizontal and vertical displacements are required at the dam crest, and upstream and downstream toe locations for embankment dams. Surface displacement monuments should be located to provide coverage across the length of the dam extending to the adjacent stable areas. Provisions should be made to detect relative and absolute movement of armor on the dam face. Typically, the spacing of points near abutments and appurtenant structures are closer by about 50 percent than for the points at the midsection of the crest to provide denser movement data with respect to the surrounding sides, spillways, and foundation areas. New or temporary monitoring points may be concentrated in areas where significant movement is detected or repairs are underway.

(6) Navigation lock monoliths. Monitoring points are set on each lock chamber wall, typically with at least two alignment pins situated close to each monolith joint on each wall. The centerline of the alignment pins are placed in a longitudinal alignment between at least two major monumented control points to facilitate making deflection/offset alignment measurements--see Figures 2-4 and 2-5. Alignment pins are placed after proper curing of the structural concrete, and set back about six (6) inches perpendicularly from the centerline of the monolith joint, with one bolt located on either side of the joint.

2-10. Design of Reference Networks

a. General. Having multiple control stations in the reference network is critical for improving the reliability of deformation surveys, and for investigating the stability of reference monuments over time. Each control station in the reference network should be intervisible to a maximum number of structural monitoring points (placed on the structure) and to at least two other reference monuments. The number of reference points for vertical control should be not less than three (3), and preferably four (4) benchmarks. For horizontal control the minimum number of reference points should be at least four (4), preferably six (6). Reference stations are usually located at both ends of the dam, along its longitudinal axis, at the elevation of the dam crest. Geometry and reliability of the reference network can be improved by adding control stations either upstream or downstream from the crest or on the structure itself.

b. Project datum selection. A project datum defines the relative positions and coordinates established on the reference network. Coordinates of monitoring points are also calculated with respect to the project datum. The project datum for large monitoring projects should be based on geodetic NAD83 (or WGS84) coordinates. A geodetic coordinate system is recommended because positioning can be directly related to a standard reference ellipsoid. Network adjustment processing software often requires definition of the project datum in geodetic coordinates. Geodetic coordinates are also compatible with standard formulas used to transform 3D positions into two-dimensional plane projections, and can incorporate data from Global Positioning System (GPS) surveys. See Figures 2-2 and 2-3.

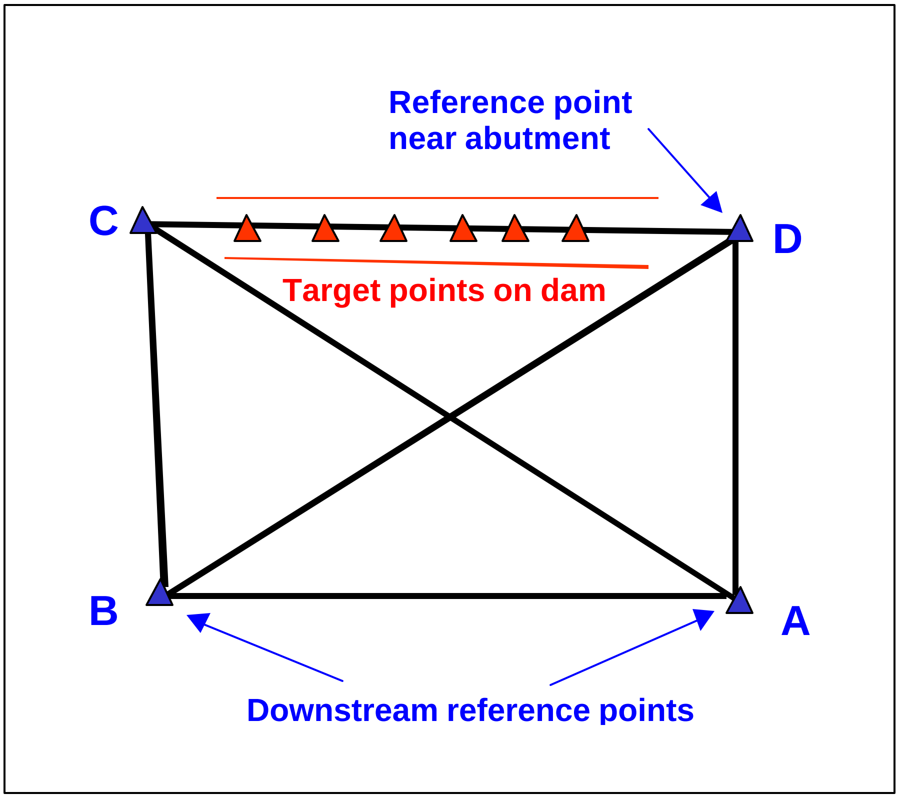

Figure 2-2. Strong monitoring scheme for a concrete or earth/rockfill dam

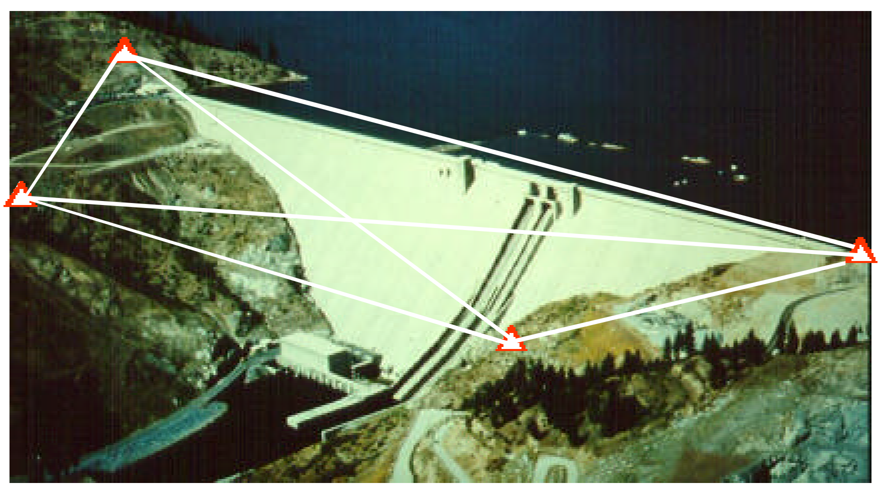

Figure 2-3. Reference network configuration for a concrete dam depicting reference points near abutments and at downstream locations

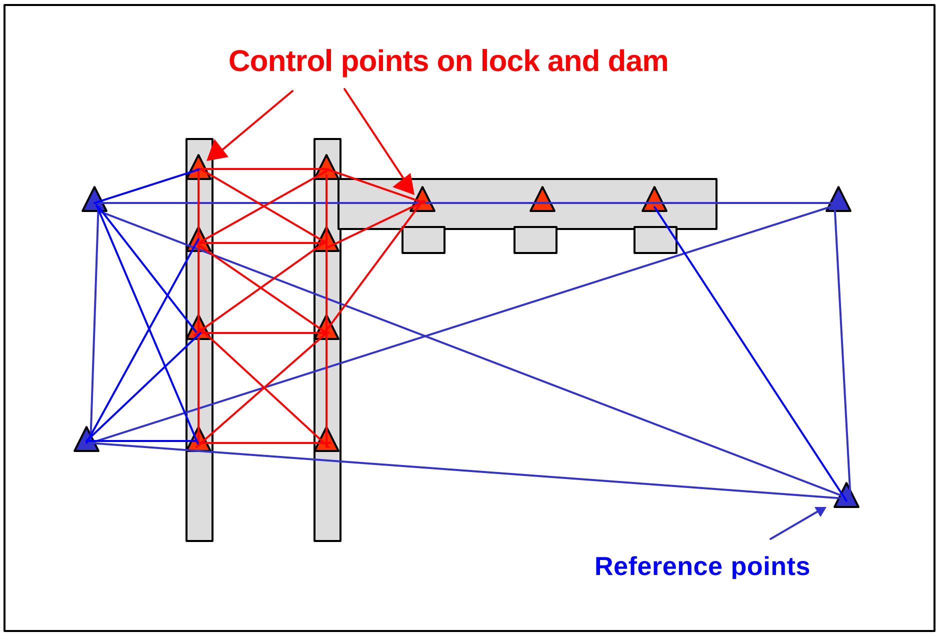

Figure 2-4. Strong monitoring scheme for a lock and dam

Figure 2-5. Idealized monitoring scheme for controlling target points on the lock and dam

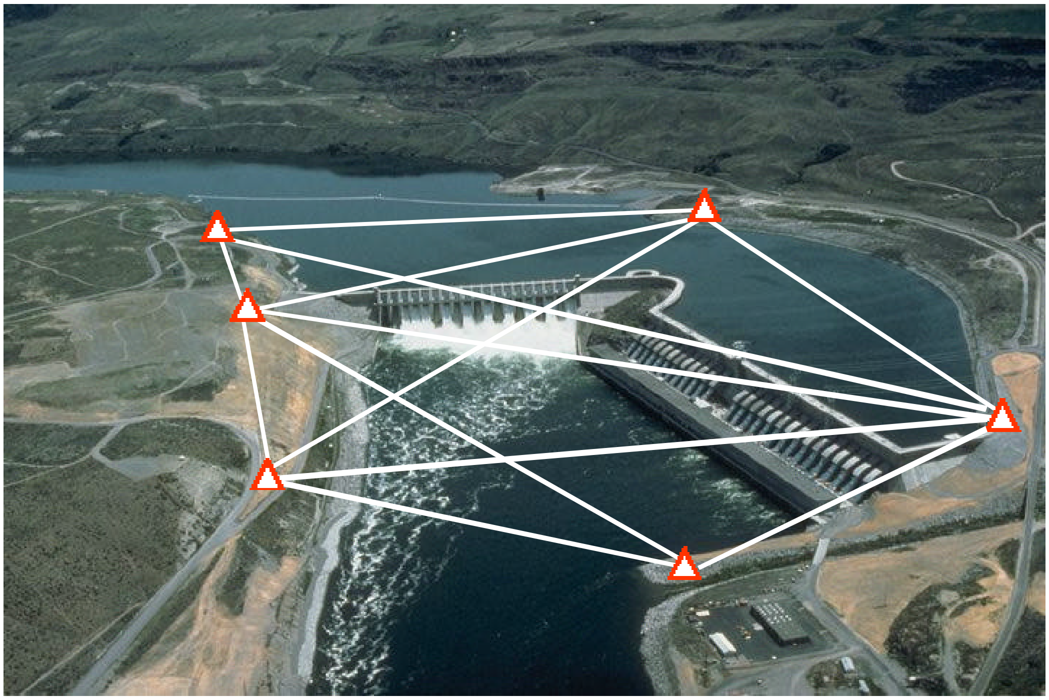

Figure 2-6. Idealized reference network surrounding a hydroelectric dam. External reference points are established at downstream points and on reservoir to provide strong geodetic network

(1) Reference station coordinates. Coordinates are initially established on at least one or two stations in the reference network from National Geodetic Reference System (NGRS) control monuments available in the local area. Coordinates are then transferred by direct measurement to the remaining stations in the reference network before the first monitoring survey. 3D coordinates should be established on all structure control points and reference stations for projects that combine horizontal and vertical positioning surveys.

(2) Monitoring point coordinates. Geodetic or state plane coordinate systems are recommended for monitoring networks because standard mapping projection will provide consistency in coordinate transformations. Arbitrary coordinate systems based on a local project construction datum are more difficult to work with if there is a need for transforming from the local datum. Independent vertical positioning surveys are needed to augment 2D horizontal positioning networks. Vertical settlements are then computed apart from the horizontal displacement components.

c. Reference network stability. Reference network stations can be independently measured using higher precision survey methods than used for the general monitoring network. The reference network survey is also analyzed in a separate network adjustment to check for any change in reference station coordinates between monitoring campaigns. GPS technology alone, or GPS combined with high precision EDM distance measurements is suggested for reference network stability monitoring. Multiple EDM distance ties provide additional network redundancy as an external check on the GPS results. Detection and analysis of unstable reference points in the reference network has been successfully implemented using the Iterative Weighted Similarity Transformation (IWST). This analysis indicates whether any particular reference station has experienced significant movement between monitoring surveys by transforming observed displacements independent of the network constraints.

2-11. Reference Point Monumentation

a. General. A monument used for deformation monitoring is any structure or device that defines a point in the survey network. Monuments can be classified as either a reference point or a monitoring point. A reference point typically is located away from the structure and is to be "occupied" during the survey, while a monitoring (or object) point is located directly on the structure and is to be "monitored" during the survey. Each must have long term stability of less than 0.5 mm both horizontally and vertically with respect to the surrounding area. A permanent one (1) mm diameter reference mark, or forced centering device, should be used for every monitoring point monument. Further information on specific monument design and installation is provided in EM 1110-1-1002, Survey Markers and Monumentation.

b. Reference point monuments. Reference points can be either a steel pipe pile or cast-in-place reinforced concrete pile--Figure 2-7. If a steel pipe pile is used, the nominal diameter will be no less than 20 cm, while the wall thickness will be no less than that for standard weight pipe. If using a cast-in-place reinforced concrete pile, the nominal diameter will also be no less than 20 cm (Figure 2-8).

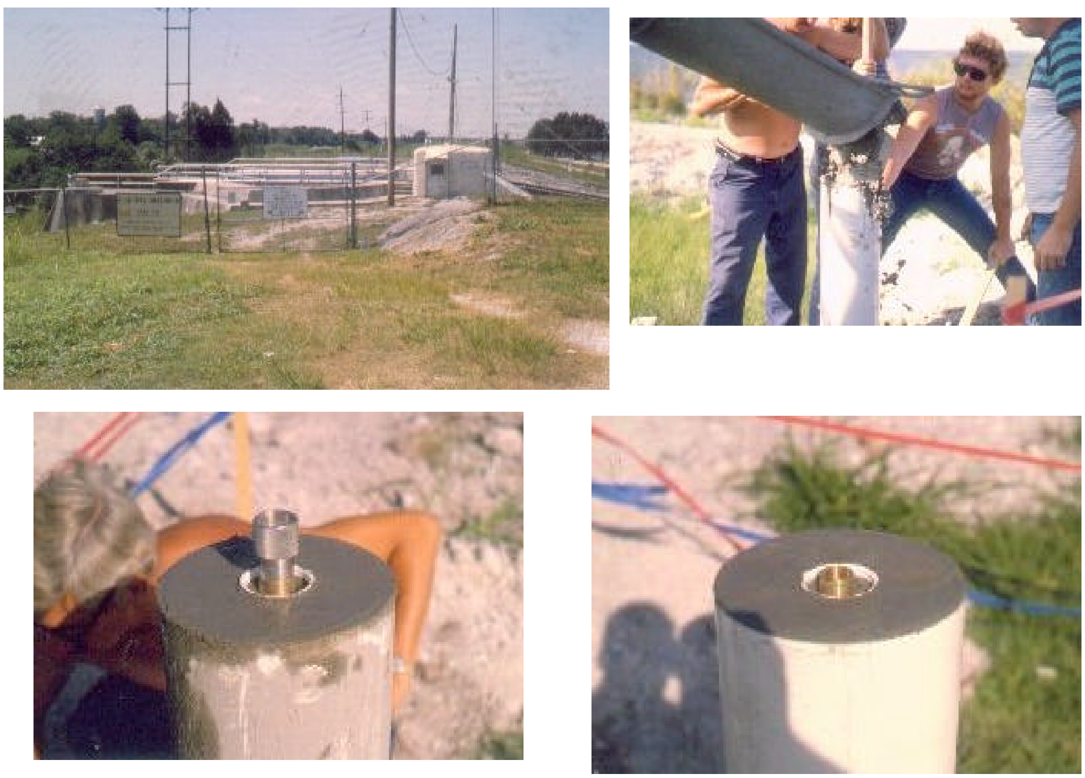

Figure 2-7. Reference point monumentation. Concrete pier construction vicinity of a hurricane gate structure. Forced centering plug set into concrete pier. (Jacksonville District)

c. Reference point installation. Reference points placed in the earth are installed to a depth equal to at least twice the depth of frost penetration in the project area. The reference point extends above ground level to a convenient height (e.g., 1.5 m) where the equipment can be force centered. Typically, at the top of such a reference point pile, a stainless steel plate not less than 2 cm thick is cast into the top of the pile using a minimum of four steel reinforcing bar anchors welded to the underside of the plate. In the center of the plate, a 5/8 inch diameter 11NC steel bolt is welded to the plate to allow survey equipment to be attached.

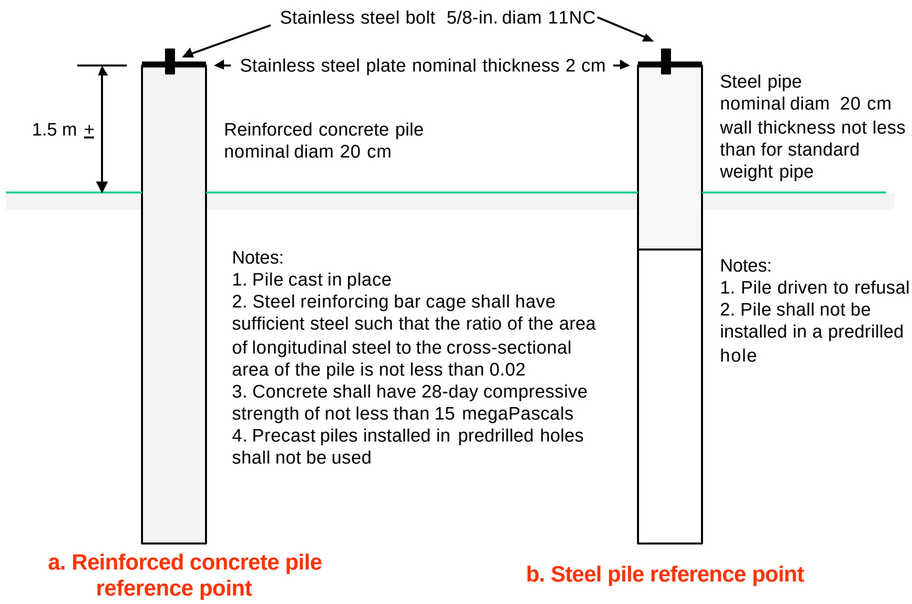

Figure 2-8. Reference point monumentation. Detail for reinforced concrete pile or steel pile construction

(1) Steel pipe pile. A steel pipe pile is installed by driving it until refusal. If refusal occurs at a depth of less than twice the depth of frost penetration in the project area, the pile is removed and its installation attempted in another location. Steel pipes placed in over sized pre-drilled holes and backfilled will not be used as reference points. For pipe piles terminating at or slightly below ground level, a convex stainless steel plate and stub will be installed as described above. The plate will be convex as required for leveling observations and will have an etched cross at the highest point of the convex surface for horizontal observation. It is recommended that such piles also have a cylindrical rim and cover around it for protection. If a cylindrical rim and cover is used, it is further recommended the cover be buried for easy recovery with a metal detector, as well as to minimize the chance of vandalism.

(2) Cast-in-place reinforced concrete pile. A cast-in-place reinforced concrete pile is installed by first drilling a hole to at least twice the depth of frost penetration in the project area. The cage of steel reinforcing bars used will have cross-sectional area of steel to concrete of not less than 0.02. After the cage is formed, it is placed in the hole. Concrete with a 28-day compressive strength of not less than 15 megaPascals is then poured into the form. Precast reinforced concrete piles driven into pre-drilled holes or placed in oversized pre-drilled holes and backfilled will not be used for reference points. Reference points installed in rock or concrete consist of a stainless steel plate as described above, except with a steel reinforcing bar stub welded to the underside. For installation, a hole at least 50% larger than the stub is drilled into sound rock or concrete. The plate with the stub attached is secured to the rock or concrete using adequate epoxy adhesive to completely fill the void between the stub and the rock or concrete.

(3) Insulation. Projects subjected to cold weather conditions will have an insulation sleeve installed around the reference point pile that extends above the ground. The installation of a sleeve is to eliminate the possibility of temperature induced pile movements that may be the result of solar radiation (i.e., temperature variation due to time of day). When this is the case, the sleeve should have an R value of not less than 10.

(4) Stability. If possible, the reference points should be installed at least a year prior to their use to minimize the effects of pile rebound and shrinkage. If this is not practical, no less than a month prior to its use will suffice.

2-12. Monitoring Point Monumentation

a. Monitoring point marks. Monitoring points installed in earth consist of a nominal 3 m length of square steel hollow structural section with a nominal side length of 5 cm and a wall thickness not less than that for a standard weight square steel hollow structural section. The base of the section is sharpened by cutting it at a 45 degree angle. Welded approximately 15 cm from the base is one length of 10 mm thick 20 cm diameter circular helix with a pitch of 7 cm. Welded to the top of the pipe is a steel plate not less than 5 mm thick. In the center of the plate a 5/8 inch 11NC steel bolt on to which survey equipment is to be connected is drilled through and welded to the plate. Some method (e.g., through the use of a cap) should be used to protect the threads of the bolt during the time survey equipment is not attached.

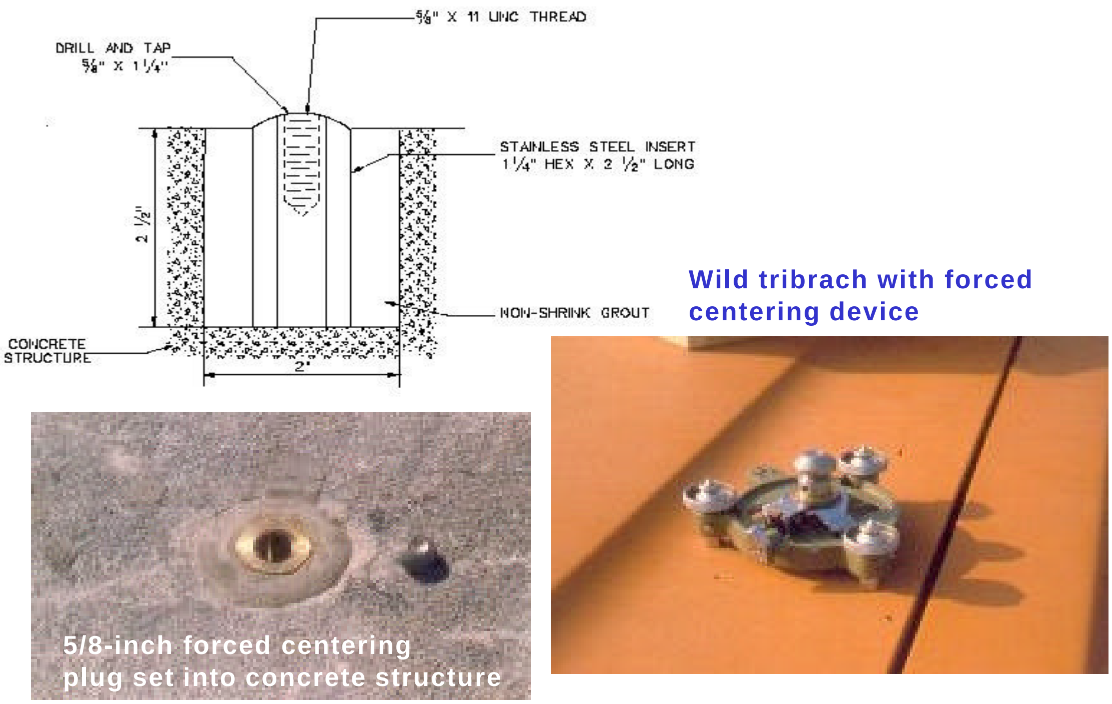

Figure 2-9. Target plug set on concrete structure. Forced centering device on tribrach shown upside down

b. Monitoring point installation. Monitoring points set directly in rock or concrete may be either a steel bolt or a steel insert into which survey equipment is force centered--see Figure 2-9. Installation of these types of monuments is as follows:

(1) Steel bolt. The steel bolt is drilled through and welded to a 5 cm diameter, 1 cm thick steel plate. A steel reinforcing bar stub of suitable length is welded to the head of the bolt. A hole approximately 50% larger than the stub is drilled in sound rock or concrete. The plate with the stub attached is secured to the rock or concrete using adequate epoxy adhesive to completely fill the void between the stub and the rock or concrete. The threads of the bolt should be protected during the time survey equipment is not attached (e.g., by use of a cap).

(2) Steel insert. Steel inserts have been designed as commercial off-the-shelf items. Manufacturer instructions for proper installation of the insert should be followed.

(3) Other materials. Monitoring points on materials (e.g., steel, masonry, etc.) other than described in the previous paragraphs will be permanently affixed. For object points to be mounted on steel, a steel bolt welded to the steel may be suitable. For masonry, or other material, a steel bolt, plate and rear stub or a steel insert may be suitable.

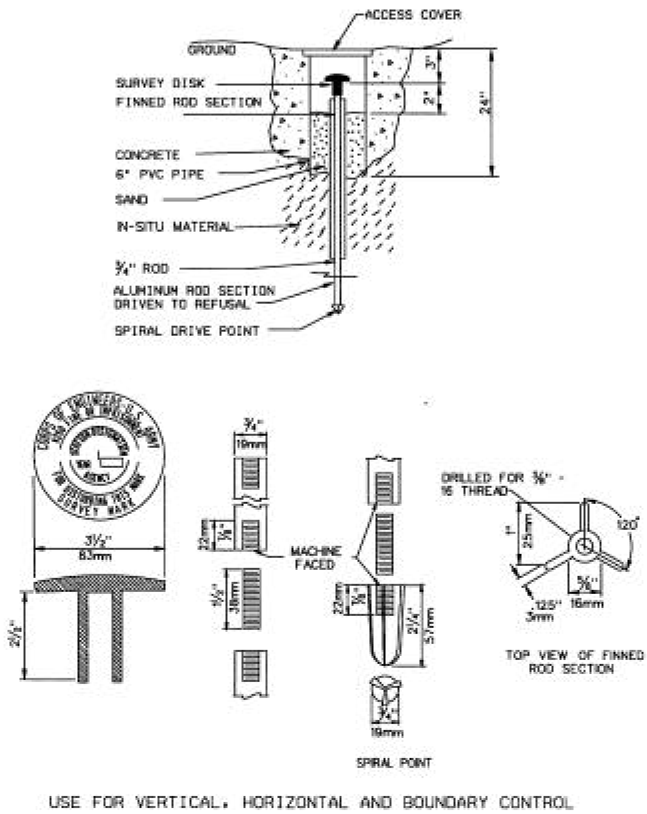

Figure 2-10. External deep-driven benchmark design--for vertical control only

c. Monitoring point targets. A target is a device with a well-defined aiming point that is placed vertically over or attached to a monument. The purpose of a target is to connect the measurement to a physical object. A target is typically installed only for the period of the survey, in some cases, the monument may be a target itself.

(1) Optical theodolites. Force-centered, standard target sets designed for one second theodolites, or the actual reference mark on the monument itself can be used as a target.

(2) Electronic total station. Force-centered, standard target set/prism combination used with a particular total station. Target set/prism combinations not matched to a particular total station will not be used. Target set/prism combinations for total stations which are non-coaxial, will be tilting target set/prism combinations that allow for alignment with the line of observation.

(3) EDM prisms. EDM targets will be the reflectors included with the EDM unit. Prisms not matched to a particular EDM will not be used.

(4) Chaining points. Targets for taped distances will be the monuments themselves.

(5) Leveling points. Targets for leveled height difference measurements will be the monuments themselves. If the monuments are steel inserts, the targets will be stainless steel plugs designed for the purpose. If more than one plug is to be used on a project, the plugs will be of the same size. Standard vertical control benchmarks may also be used, as shown in Figure 2-10.

(6) Panel points. Photogrammetric survey targets will consist of a high contrast, white dot on a black background. The diameter of the white dot is chosen so as to yield an average image diameter of 60 microns. The black background typically is 5 times the diameter of the white target.

(7) GPS reference marks. Targets for GPS surveys shall be the monuments themselves. Antenna offsets will be measured to relate the antenna phase center to the station marks.

d. Identification. A unique identifier (e.g., numeric or alphanumeric) will be stamped on the point as appropriate for all installed reference and monitoring points. Permanent records will be kept of the identifier, description, location and condition of each reference and monitoring point.

2-13. Design of Measurement Schemes

a. Optimal design methods. The optimization of *geodetic positioning* networks is concerned with accuracy, reliability, and economy of the survey scheme as the design criteria. Design of *deformation monitoring* schemes is more complex and differs in many respects from the design of simple positioning networks. Monitoring design is aimed at obtaining optimum accuracies for the deformation parameters (e.g. strain, shear, rotations, etc.), rather than for the coordinates of the monitoring stations. This allows using various types of (geodetic and non-geodetic) observables with allowable configuration defects. Multi-objective analytical design methodologies are known but not presently implemented within USACE because their practical application has not been demonstrated in any real-life examples. These techniques allow for a fully analytical, multi-objective optimal design of integrated deformation monitoring schemes with geodetic and geotechnical instrumentation. The method gives a simultaneous solution for the optimal configuration and accuracy of the monitoring scheme according to the given criteria and restrictions concerning the locations of some observation stations and required accuracy of the deformation parameters.

b. Expected movement thresholds. The design of deformation surveys from simple positioning accuracy criteria requires knowledge of the maximum expected displacement for all monitoring points on the structure. The amount of expected deformation is predicted using either deterministic modeling (by finite or boundary element methods), or empirical (statistical) prediction models. For example, predicted displacements from an engineering analysis may be documented in design memorandums prepared for construction, or from displacement trends established by geotechnical instruments. Displacements predicted at specific monument locations are requested from design engineers and then documented in the Instrumentation Plan.

c. Accuracy requirements. Positioning accuracy required for each monitored point is directly related to the maximum expected displacement occurring under normal operating conditions. Accuracy requirements are computed by equating the maximum allowable positioning error to some portion of the total magnitude of movement that is expected at each point. Specifically, the positioning accuracy (at the 95% probability level) should be equal to one fourth (0.25 times) the predicted value of the maximum displacement for the given span of time between the repeated measurements. Maximum possible accuracy is required once any abnormal deformations are noticed. With higher accuracy measurements it is easier to determine the mechanism of any unpredicted deformations. Therefore, monitoring surveys may require updating of the initial measurement design over the duration of the monitoring project.

d. Survey error budget. The basis for computing the allowable survey error budget is as follows:

(1) Accuracy should be less than one-third of the predicted value for the maximum expected displacement (D_{max}) over the given span of time between two surveys. This ensures that the total uncertainty in coordinates (plus and minus) is less than two-thirds of the total predicted movement as a minimum safety factor.

$$P_{error} < (1/3)\, D_{max} \qquad \text{(Eq 2-1)}$$

where

P_{error} = allowed positioning error
D_{max} = maximum expected displacement

(2) Displacements are calculated by differencing coordinates obtained from two monitoring surveys. Therefore, the total allowable displacement error (σ_d) must combine uncertainty in both the initial (σ_1) and final (σ_2) surveys:

$$\sigma_d = \text{sqrt}\,(\sigma_1^2 + \sigma_2^2) \qquad \text{(Eq 2-2)}$$

where

σ_1 = positioning uncertainty of initial survey
σ_2 = positioning uncertainty of final survey

Positioning accuracy will be approximately equal (σ_0) if the same methods and instruments are used on each survey:

$$\sigma_0^2 = \sigma_1^2 = \sigma_2^2$$

and

$$\sigma_d = \text{sqrt}\,(2) \cdot (\sigma_0) \qquad \text{(Eq 2-3)}$$

Therefore, the error budget should be divided by a factor of the square root of 2.

$$P_{error} = (\sigma_d) / \text{sqrt}\,(2)$$

(3) The developments above assume positioning uncertainty at the 95 percent confidence level.

$$P_{95\%} < [\,(1/3)\, D_{max}\,] / \text{sqrt}\,(2) \qquad \text{(Eq 2-4)}$$

or approximately $P_{95\%} = (0.25)\,(D_{max})$. Expressed as a standard error (one-sigma value), it would need to be divided by the univariate confidence level expansion factor of 1.96, and changed to:

$$P_{one\text{-}sigma} < [\,(1/3)\, D_{max}\,] / [\,\text{sqrt}\,(2)\cdot(1.96)\,] \qquad \text{(Eq 2-5)}$$

or approximately $P_{one\text{-}sigma} = (0.12)\,(D_{max})$.

(4) Accuracy Requirement Example. To detect an expected displacement component of x mm from two independent monitoring surveys (same methods), it should be determined with an accuracy of:

$(x / 3) / (1.41) \sim x / 4$ mm, at the 95 percent confidence level, or
$(x / 4) / (1.96) \sim x / 9$ mm, at one standard error.

As a 'rule of thumb,' the measurements of a deformation component should be performed with a standard deviation (an error at one-sigma level) about nine (9) times smaller than the expected maximum value of the deformation. At the 95 percent confidence level this equates to approximately four (4) times smaller than the expected maximum value of the deformation.

e. Network preanalysis. Two closely related techniques for processing survey data are *preanalysis* and *adjustment* of geodetic networks.

- Preanalysis is a measurement design technique used to statistically verify whether a proposed monitoring survey meets pre-set accuracy requirements. It requires the user to choose approximate coordinates for each survey point, plan a desired measurement configuration, and assign a standard deviation to each measurement based on instrument specifications. Preanalysis yields an expected precision for each monitoring station in the network for a given survey design.

- Adjustment requires the user to process actual survey data. Usually data is collected according to the same measurement scheme developed from preanalysis. Survey adjustment yields best-fit coordinates and precision for each monitoring station in the network.

Both preanalysis and adjustment use the same underlying mathematical model to produce results. Although the required computations are complex, this problem is always transparent to the user because processing is done by software applications. Preanalysis specifies the expected positioning uncertainty based on random error only, therefore, a weight is assigned to each survey measurement based on its predicted standard deviation, which is computed *a priori* using known variance estimation formulas. Measurement uncertainties are propagated mathematically into a predicted error value for each station coordinate. This error is reported graphically by a point confidence ellipse, or by a relative confidence ellipse between two points. Each point confidence ellipse (error ellipse) encloses a region of maximum positioning uncertainty at a given statistical confidence level (usually 99-percent for preanalysis and 95-percent for adjustment). The corresponding vertical positioning error is reported by a point confidence interval for each point. Once accuracy requirements are specified for positioning the monitoring points, different survey designs can be proposed, tested, and modified until the coordinate error becomes small enough to detect a target level of movement based on accuracy requirements. Instruments used for each survey design are then selected based on the preanalysis results. Refinements to the survey design are made by judiciously adding or removing observations to create a finished measurement scheme. Once the accuracy performance of each survey design has been verified, the selected instruments, the number and type of measurements, and the survey network layout can be specified for field data collection.

2-14. Measurement Reliability

a. General. Reliability addresses the geometric strength of the observation scheme, measurement redundancy, and techniques for minimizing measurement biases. Statistical methods can determine the maximum level of undetected systematic error using outlier detection. Some reliability factors are:

- Redundant measurements,
- External checks on the validity of the data,
- Instrument calibrations,

- Reference network stability analysis,
- Rigorous data processing techniques,
- Multiple connections between stations.

b. Redundancy. Multiple sources of monitoring data (instruments and observations) allow for checking the consistency of deformation surveying measurements. Redundancy on monitoring surveys provides a means to check results, such as by collecting twice as many measurements as unknown coordinates, and by keeping parallel but separate sets of instruments that use different measurement methods. For example, relative displacements can be obtained from tiltmeters and geodetic leveling. A properly designed monitoring scheme should have a sufficient connection of measurements using different measuring techniques and such geometry of the scheme that self-checking through closures would be possible. Redundancy is also a requirement for using least squares adjustment techniques in data processing.

c. Instrument calibrations. Calibrations of surveying instruments are highly standardized and are essential for valid results when coordinate differencing is used to compute displacements. Major sources of systematic error and types of calibrations and procedures are presented in Chapter 4.

d. Stable point analysis. Accuracy in displacement measurements depends greatly on the stability of the network of reference stations. The reference network survey is analyzed separately to detect unstable reference stations in monitoring networks (see references listed in Section A-2 of Appendix A).

e. Rigorous data processing. Most surveying observations will require post processing before being used in a network adjustment or in the calculation of final displacements, e.g., for the elimination of nuisance parameters and the management of various data reductions and transformations. Some of the available reduction formulas are more accurate and complete than others. In general, the more rigorous version of a given formula is recommended for processing data on deformation networks.

f. Design of complex monitoring schemes. Survey networks can be broken down into several sub-networks to obtain specialized deformation information where each small piece can be analyzed in separate network adjustment, or so that measurements made on an isolated structural element can be connected to the whole. Dividing the network into distinct parts makes it simpler to isolate and identify gross errors and provides for additional observations between each sub-network to strengthen the overall measurement scheme. Specialized sub-networks increase the reliability of the survey results.

(1) Cross-sections. Surface monuments can be co-located with geotechnical instrumentation that are installed on the interior of the structure (e.g., service galleries of a dam). Geodetic monitoring points and fixed instrumentation placed on the same monolith provides the monitoring scheme with a high degree of redundancy.

(2) Survey sub-networks. Monitoring networks can be broken down into different types of smaller surveys (i.e., networks).

- *Regional reference network* established by a few widely distributed, off-site, reference points to provide regional information in seismically or geologically active areas;

- *Main reference network* of project reference points, situated in stable areas surrounding the structure, are used as a base to survey the monitoring points on the structure. The reference network is surveyed independently to investigate the stability of the reference stations, and to obtain higher accuracy of the coordinates of the reference stations.

• *Secondary network* of control monuments, installed directly on the structure, provides for a system of measurement ties between each other (i.e., between other structure control points). Control points in the secondary network are inter-connected by measurements and are also directly connected by measurements to the main reference network. For example, on navigation locks, angles and distances could be observed between secondary control points on adjacent lock walls, to tie together the separate alignment sections that are installed on each lock wall.

• *Localized networks* consist of the major body of survey monitoring points, grouped between secondary control points, for example, sections of multiple alignment pins that are placed between two control points on the structure. Such localized surveys provide monitoring coverage over the entire structure and in any critical areas. Alignment section surveys are examples of localized networks, as well as the point data gathered from localized instrumentation such as jointmeters or plumbline stations.

(3) Seismic network stations. Pre-surveyed positions can be established on any number of additional localized monitoring points (i.e., points not intended for routine observation) to determine the nature and extent of large displacements due to earthquakes. Continuous geodetic measurements also can be used for monitoring the consequences of seismic activity. One or more points on the structure are connected to a regional reference network, such as wide-area GPS arrays used for tectonic studies.

2-15. Frequency of Measurements

a. General. Geodetic monitoring surveys (for periodic inspections) are conducted at regular time intervals rather than by continuous measurements that are more typical of automated structural or geotechnical instrumentation. The time interval between deformation surveys will vary according to the purpose for monitoring, but is generally correlated to condition of the structure. Design factors such as the structure's age, hazard classification, safety regulations, and probability of failure determines an appropriate frequency for surveys, or the need for establishing more frequent survey campaigns.

b. Continuous monitoring. With automatic data acquisition, such as by DGPS or robotic total stations, the frequency of measurements does not impose any problem because the data can be decoded at a pre-programmed time interval without difficulty and at practically no difference in cost of the monitoring process. Continuous monitoring systems with geodetic measurements are not yet commonly used and the frequency of measurements of individual observables must be carefully designed to compromise between the actual need and the cost.

c. Age-based criteria. Guidelines for the frequency for conducting monitoring surveys (e.g., International Committee on Large Dams) follow a time table based on the age of the structure.

(1) Pre-construction. It will be useful to carry out some geodetic and piezometric measurements of the abutments before and during construction.

(2) Initial filling. A complete set of measurements should be made before the first filling is started. The dates of successive measurements will depend on the level the water has reached in the reservoir. The closer the water is to the top level, the shorter will be the interval between measurements. For instance, one survey should be conducted when the water reaches 1/4 of the total height; another survey when the water reaches mid-height; one survey every tenth of the total height for the third quarter; one survey every 6 ft of variation for the fourth quarter. The interval between two successive surveys should never exceed a month until filling is completed.

(3) Stabilizing phase. Measurements should be more frequent in the years immediately following the first filling when active deformation is in progress. Geodetic surveys can be carried out four times a year and other geotechnical measurements can be made once every 1 to 2 weeks.

(4) Normal operation. After the structure is stable, which can take up to 5 to 10 years or more, the above frequencies can be reduced by half. The frequencies of measurement can be reduced further according to what is learned during the first years of operation.

(5) Remedial phase. Once a structure begins showing significant signs of stress or advanced deterioration, measurement frequencies based on the stabilizing phase can be resumed to track potential failure conditions. It should be possible to conduct intensive investigations in areas undergoing the most critical distress to determine the causes of the deformations and plan for repairs.

d. Hazard based criteria. The frequency for conducting monitoring surveys are related to the hazard classification. Table 2-2 recommends monitoring frequency according to the hazard classification (HIGH, MEDIUM, or LOW) assigned to the structure.

Table 2-2. Structure Classification

<table>
<tr><td colspan="2">STRUCTURES IN DISTRESS</td><td colspan="4">STRUCTURES NOT IN DISTRESS</td></tr>
<tr><td colspan="2">Class I: HIGH RISK</td><td colspan="2">Class II: MEDIUM</td><td colspan="2">Class III: LOW</td></tr>
<tr><td colspan="2">CONTINUOUS MONITORING</td><td colspan="2">MONITOR YEARLY OR EVERY OTHER YEAR</td><td colspan="2">MONITOR EVERY OTHER YEAR</td></tr>
<tr><td>Type A</td><td>POTENTIAL FAILURE IMMINENT</td><td rowspan="2">Type A</td><td rowspan="2">Large Structures</td><td rowspan="2">Type A</td><td rowspan="2">Large Structures</td></tr>
<tr><td>Type B</td><td>POTENTIAL FAILURE SUSPECTED</td></tr>
<tr><td>Type C</td><td>DAMS OR RESERVOIRS UNDERGOING INITIAL IMPOUNDMENT</td><td>Type B</td><td>Smaller Structures</td><td>Type B</td><td>Smaller Structures</td></tr>
</table>

(1) Class I: HIGH RISK STRUCTURES. The high risk of Class I structures may warrant continuous monitoring of the structure.

(a) Type A: Potential Failure Imminent. Gather data as prudent. Data is very valuable for later analysis of why the structure failed. Use any method available to gather data without risk of life or interference in processes ongoing to save the structure and/or alert the population at risk.

(b) Type B: Potential Failure Suspect. Monitor structure continuously. After potential solution to save structure is applied, use continuous monitoring until is determined that structure is stabilized.

(c) Type C: Dams or Reservoirs Undergoing Initial Impoundment. Gather initial data before impoundment procedures start. Monitor continuously until failure is suspected or until impoundment procedures have halted. Continue monitoring continuously until it is determined that structure has stabilized and will maintain as planned under load.

(2) Class II: MEDIUM RISK STRUCTURES. Such structures are of a category of risk such that monitoring every year to every other year is prudent. Structures of this category are stable, but whose failure would affect a population area, result in a high dollar loss of downstream property, cause a devastating interruption of the services provided by the structure.

(3) Class III: LOWER RISK STRUCTURES. Such structures are of a category of risk such that monitoring every other year is prudent. Structures of this category are stable, but whose failure would not affect a population area, not result in a high dollar loss of downstream property, not cause a devastating interruption of the services provided by the structure.

e. Risk assessment criteria. Conditions that indicate an increased probability of failure, such as, historical earthquake frequency and magnitude, predicted maximum flood stage and frequency, structure design lifetime, combined with knowledge of the expected impacts to life and property downstream can be used to assess the relative risk from different failure modes at a given project. This information can aid in determining the frequency for monitoring surveys, especially on structures that have innovative or specialized design features. Examples of certain load cases used in the analysis of stability and calculation of stresses have been categorized in EM 1110-2-2200 (Gravity Dam Design).

f. Technical instructions and scopes of work. Appendix B contains a sample contract scope of work for performing periodic deformation monitoring surveys. As is outlined in the example scope, some of the specialized monitoring instrumentation is furnished by the Government. Not all Architect-Engineer firms can be expected to have monitoring equipment on hand due to the limited requirement for such work. Often, a Government representative may be required to accompany the survey team on site.

2-16. Mandatory Requirements

The standards outlined in paragraphs 2-2 and 2-3, including Table 2-1 (Accuracy Requirements for Structure Target Points), are mandatory.